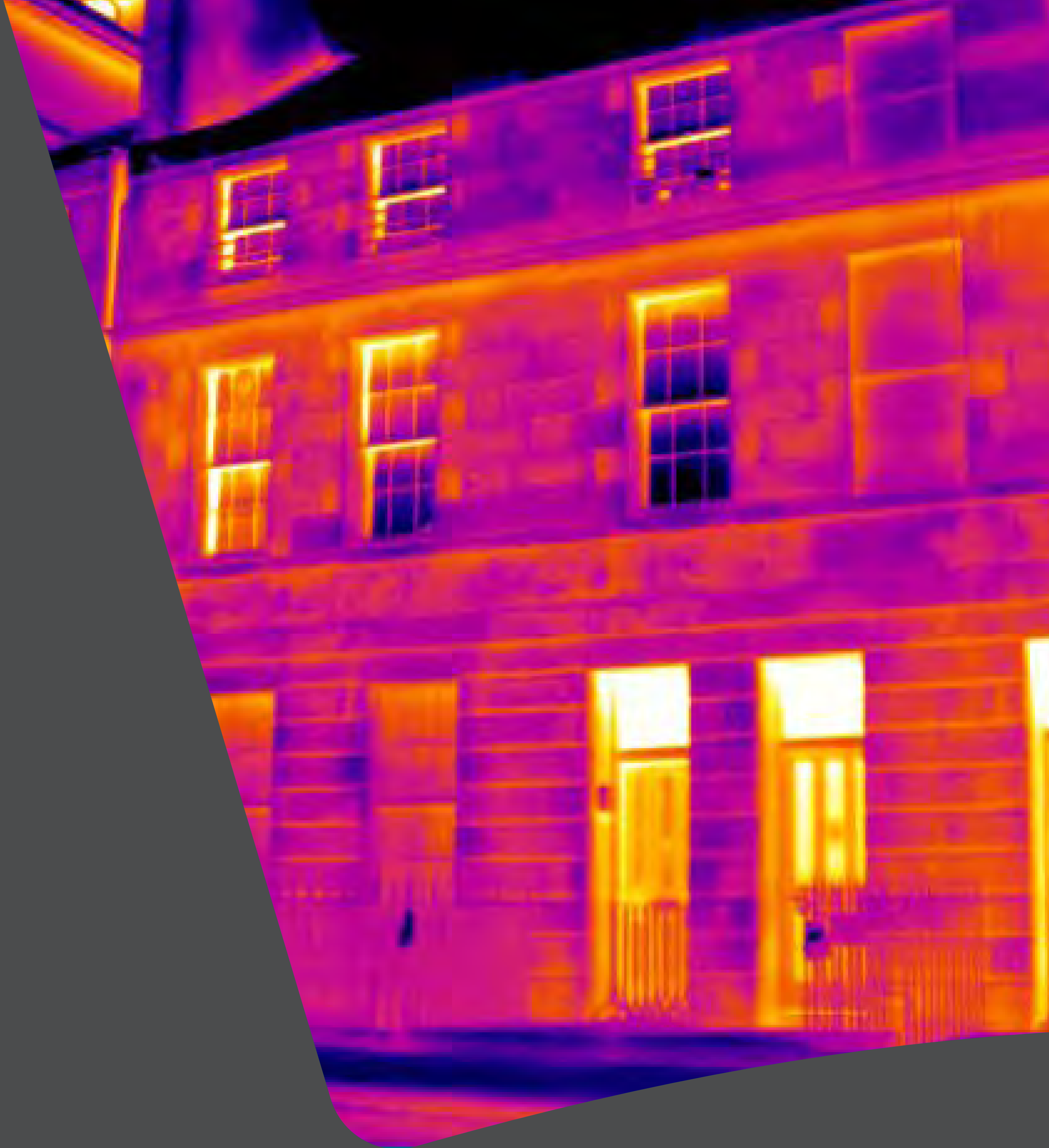

TECHNICAL PAPER 24

HISTORIC ENVIRONMENT SCOTLAND REFURBISHMENT CASE STUDIES: REVIEW OF ENERGY EFFICIENCY PROJECTS

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TECHNICAL PAPER 24

HISTORIC ENVIRONMENT SCOTLAND REFURBISHMENT CASE STUDIES:

REVIEW OF ENERGY EFFICIENCY PROJECTS

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PREFACE BY HISTORIC ENVIRONMENT SCOTLAND

Over the last decade, there has been an increased awareness of the need to improve the energy efficiency and sustainability of Scotland's building stock and to fulfil obligations under the Climate Change (Scotland) Act 2009. During this time Historic Environment Scotland has developed and implemented energy efficiency upgrades to a range of domestic and non-domestic traditional buildings to demonstrate and test how traditional buildings can be adapted to deliver improved thermal performance, reduce carbon emissions and create buildings which are more comfortable and easier to heat. This Technical Paper reports on an independent review of eighteen of Historic Environment Scotland's Refurbishment Case Studies which describe how traditional buildings have been improved, and what lessons can be learned about how best to upgrade Scotland's traditional building stock.

Each case study comprised the refurbishment of a building to improve its energy efficiency and thermal comfort. The refurbishments were carried out on a range of domestic building types including traditional cottages and tenements, and public buildings such as libraries or schools. All the buildings studied were of traditional solid wall construction, and some were listed. The proposals were not limited to energy-efficiency measures, but considered issues of sustainability, indoor environmental quality, life cycle assessment and available skills. Each case study focused on one building, or a collection of buildings, upgraded with support from Historic Environment Scotland. The refurbishments typically incorporated innovative, adapted or non-standard materials, although most are readily available on the market. The impact of the interventions on the buildings' performance and occupants' comfort forms much of this Technical Paper.

One of the aims of these case studies was to demonstrate a variety of upgrade options which, although not always directly transferable to other projects, could provide inspiration for developing creative upgrade measures suitable for the refurbishment of the existing building stock. The measures were designed above all to be minimally invasive and physically compatible with the existing building fabric in terms of maintaining ventilation and vapour permeability, and conserving historic finishes. The measures aimed to retain as much of the existing fabric, finishes and fittings as possible for reasons of both building conservation and waste reduction. This is in contrast to some conventional approaches which involve the removal of existing finishes and the use of vapour-impermeable components and finishes.

Various types of interventions are examined: insulation upgrades to roofs, walls and floors; thermal performance improvement of windows and doors; and the installation of new heating. This Technical Paper reports on the success of the interventions in terms of their current condition and performance, and the impact on the building occupants in terms of their thermal comfort and energy bills.

This Technical Paper complements other publications by Historic Environment Scotland, notably *Short Guide 1: Fabric Improvements for Energy Efficiency in Traditional Buildings* and *Short Guide 8: Micro-renewables in the Historic Environment* and should be read in conjunction with the existing range of Refurbishment Case Studies and Technical Papers which looks at individual projects and measures in more detail. Together these publications provide practical and technical information for all those working on upgrading existing buildings. The aim is to invite discussion and support decision-making in the drive to make Scotland's built heritage more energy-efficient and sustainable. The published Refurbishment Case Studies are available online on Historic Environment Scotland's website.

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1. INTRODUCTION

1.1 Background

This Technical Paper reports on the findings from a review of eighteen Historic Environment Scotland (HES) Refurbishment Case Studies which comprised works carried out to improve energy efficiency in traditionally constructed buildings dating from between the late 17th and early 20th centuries. The works were completed between 2010 and 2016.

Each case study outlined the type and construction of the building(s) being refurbished and any inherent issues which existed prior to works starting. Each of the interventions specified and the process of fitting, installing and/or application were accurately described together with any enabling works which occurred beforehand. In addition, the results of any monitoring and research undertaken before, during or after completion of the works were detailed. The most frequently presented data within the case studies were changes in U-values resulting from the interventions. These reflect changes in the thermal performance of a building element, a measure of the rate of heat transfer through the structure when the temperature on either side differs, expressed in units of Watts per square metre per degree of temperature difference (W/m^2K).

The U-values recommended within the Scottish Government's Building Standards Technical Guidance provided a useful comparative benchmark (Table 1). For historic, listed or traditional buildings, the guidance has a degree of flexibility which considers construction, form, character and maintaining key features, recommending that each is dealt with on its own terms. The guidance states that the aim should be to achieve the overall U-values recommended for the conversion of existing (a) heated or (b) unheated buildings. However, it advises that the feasibility of upgrading fabric to at least the individual element U-values given below in column (c) of Table 1 should be considered.

In addition to the U-value measurement, findings from other research and testing such as thermal imaging, air-tightness testing and indoor-air quality monitoring conducted during the trials were considered when drawing conclusions. These findings may help inform any future works of a similar nature.

Type of element	Area-weighted average U-value (W/m^{2}K) for all elements of the same type		(c) Individual element U-Value (W/m^{2}K)
	(a) Maximum U-values for conversion of heated buildings	b) Maximum U-values for conversion of unheated buildings	
Wall	0.3	0.22	0.70
Floor	0.25	0.18	0.70
Pitched roof (insulation between ceiling ties or collars)	0.25	0.15	0.35
Flat or pitched roof (insulation between rafters or roof with integral insulation)	-	0.18	0.35
Windows, doors, rooflights	1.6	1.6	3.3

Table 1: Maximum U-values applicable to the conversion of historic, listed or traditional buildings from Scottish Government's Building Standards Technical Handbook (Domestic).[1]

In 2014 the Scottish Government introduced the Energy Efficiency Standard for Social Housing (EESSH). By 2020 social rented property will be required to have the equivalent of a minimum Energy Performance Certificate (EPC) energy efficiency rating of 'C' or 'D', depending on its built form. From 1 April 2019, private rented properties will need to have an EPC rating of at least E at the point of rental, with proposals for this to be raised to a 'D' rating from 1 April 2022.

The main aim of the Refurbishment Case Study review was to visit each site to inspect the general condition of the properties and the refurbishment interventions. This was done using non-invasive survey techniques, noting any defects present and identifying cause(s). The surveys were carried out between February and April 2017. In addition, feedback was gathered from the building occupants on thermal comfort and whether the interventions had any impact on their utility bills. Each case study was reported in an agreed survey template and the findings collated to prepare this Technical Paper.

[1] Scottish Government, Scottish Government's Building Standards Technical Handbook (Domestic): Energy, June 2017, accessed June 2018 http://www.gov.scot/Resource/0052/00521754.pdf

1.2 The buildings

The properties studied in the Refurbishment Case Studies were of traditional construction, comprising external solid masonry walling and timber pitched roof structures. They had a range of roof finishes including slate, tile and, in one case, corrugated iron laid over earlier surviving thatch. The properties which underwent window and/or door upgrades had single glazed, predominantly timber sash and case windows and timber doors. All the properties had undergone varying degrees of change since their original construction. In some cases, this resulted in the loss of earlier features and finishes, and the introduction of different roof finishes and window styles.

The refurbishments were carried out on properties throughout Scotland. Seven of the eighteen case studies were located in the Edinburgh and Lothian region, four in Fife and central Scotland, three in the west, two in the northeast and two in the northwest of Scotland. Sixteen of the eighteen case studies reviewed were domestic let properties, ranging from tenement flats in city locations to detached cottages in rural settings (Figure 1). The remaining were non-domestic properties comprising a small church, primary school and library (Figure 2). All the case studies are listed in Table 2.

Property	Location	Property Type	Publication	Intervention					
				Roof Insulation	Wall Insulation	Floor Insulation	Windows	Doors	Heating
Five Tenement Flats at Roxburgh Street, Marshall Street and Drummond Street	Edinburgh	Domestic Let	Refurbishment Case Study 1		✓		✓	✓	
Wells o' Wearie	Edinburgh	Domestic Let	Refurbishment Case Study 2	✓	✓	✓	✓		
Wee Causeway	Culross	Domestic Let	Refurbishment Case Study 3	✓	✓				
Sword Street	Glasgow	Domestic Let	Refurbishment Case Study 4		✓				
The Pleasance	Edinburgh	Domestic Let	Refurbishment Case Study 5	✓			✓		
Kildonan	South Uist	Domestic Let	Refurbishment Case Study 6	✓	✓	✓	✓	✓	
Scotstarvit Cottage	Cupar	Domestic Let	Refurbishment Case Study 7	✓	✓	✓	✓		✓
The Garden Bothy	Cumnock	Domestic Let	Refurbishment Case Study 8	✓	✓	✓	✓	✓	✓
Leighton Library	Dunblane	Public Library	Refurbishment Case Study 9	✓					
Two properties at Columshill Street and Russell Street	Rothesay	Domestic Let	Refurbishment Case Study 10		✓		✓	✓	
Main Street	Newtongrange	Domestic Let	Refurbishment Case Study 11	✓			✓		
Kirkton of Coul	Aboyne	Domestic Let	Refurbishment Case Study 16	✓	✓	✓			
Kilmelford Church	Kilmelford	Church	Refurbishment Case Study 19						✓
Annat Road	Perth	Domestic Let	Refurbishment Case Study 20	✓	✓	✓			✓
Downie's Cottage	Braemar	Domestic Let	Refurbishment Case Study 22	✓	✓	✓			✓
Archibald Place	Edinburgh	Domestic Let	Technical Paper 9				✓		
Lauriston Terrace	Edinburgh	Domestic Let	Pending Publication		✓				
East Linton Primary School	East Linton	School	Pending Publication	✓	✓		✓	✓	✓

Table 2: Refurbishment Case Study properties and the range of interventions carried out. The case studies are available at www.historicenvironment.scot/refurbishment-case-studies except Archibald Place which was part of a Technical Paper, available here. Case studies on Lauriston Terrace and East Linton Primary School are pending publication.

Figure 1: Domestic buildings such as Wee Causeway, described in Refurbishment Case Study 3, were included in the project review.

Figure 2: Non-domestic buildings, such as Leighton Library, were also included in the project review. This Refurbishment Case Study is pending publication.

2. RANGE OF INTERVENTIONS

The range of interventions carried out during the refurbishment upgrades can be grouped into seven categories: walls, roofs, floors, windows, doors, heating and other measures. Principally, the selection of materials and approaches specified sought to improve thermal performance by using vapour permeable materials to allow the building fabric to breathe, whilst retaining as much of the original fabric, finishes and fittings as possible.

2.1 Wall insulation

Thirteen case studies had wall insulation interventions carried out. The different insulating materials which were specified can be categorised into three methods of application:

Internal cavity fill: The void between the plaster linings and the inner face of the external masonry was filled with insulation. Four different materials, all vapour-open to allow dissipation of moisture through evaporation and diffusion, were specified using this approach: Icynene (an open cell water based foam insulation) as seen in Figure 3, polystyrene beads, cellulose and perlite. The first three materials were injected or blown into the cavity through holes drilled into the plaster linings, while the perlite insulation was poured into the cavity from an accessible attic space above (Figure 4).

Infill insulation: In case studies where internal finishes were already lost or compromised, hemp and wood fibre insulation were fitted into timber framing and cavities behind the linings before reinstating the finishes (Figure 5).

Surface applied insulation: Three surface applied materials were specified. Aerogel blanket, a relatively new lightweight product with low thermal conductivity, and calcium silicate board were fixed to existing wall surfaces and plastered over. Insulated lime plaster was applied directly on to the inner face of the external masonry at Downie's Cottage to improve thermal efficiency while replicating earlier plaster finishes (Figure 6).

Figure 3: Insulation behind existing wall linings in the form of open cell foam (Icynene) at Annat Road (photo courtesy of Historic Environment Scotland).

Figure 4: Pouring perlite insulation into wall void from the attic space at Scotstarvit Cottage (photo courtesy of Historic Environment Scotland).


Figure 5: Wood fibre board insulation fitted into a frame at Kildonan (photo courtesy of Historic Environment Scotland).


Figure 6: Surface applied insulated lime plaster at Downie’s Cottage (photo courtesy of Historic Environment Scotland).

Thermal performance: Comparison of pre- and post-intervention U-values

Pre- and post-intervention sets of wall U-values were recorded and reported upon for ten case studies, averaging an improvement of 58.3% in thermal efficiency (Table 3). Considerable improvements were made using wood fibre and hemp fibre board, recording improvements of between 52% and 83%. 100mm of hemp insulation recorded a U-value of 0.22 W/m^2K and 80mm of wood fibre recorded a U-value of 0.19 W/m^2K, both well within the Scottish Government's Building Standard guidance for maximum U-value of 0.3 W/m^2K for conversion of heated buildings.

Injected or blown cavity fill insulation materials also resulted in significant improvements. Polystyrene beads gave U-values ranging from 0.3 to 0.8 W/m^2K, an average improvement of around 50%. Blown cellulose gave an average improvement of 70%, with significant improvements of 74% and 89% recorded at Sword Street and Kirkton of Coull respectively. In both instances U-values met the guidance for maximum U-value of 0.3 W/m^2K. At Annat Road, Icynene improved the U-value of the external walls by 63%, at 0.41 W/m^2K.

Surface applied calcium silicate board averaged improvements of 67%, with U-values of 0.4 W/m^2K when applied to a depth of 50mm, and 0.7 W/m^2K at 15mm. Aerogel also recorded better levels of thermal efficiency when applied to a depth: 50mm recorded a U-value of 0.32 W/m^2K, compared with an average of 0.8 W/m^2K at 10mm. The insulated lime plaster applied at Downie's Cottage improved the U-value by 35%, from 1.8 W/m^2K to 1.1 W/m^2K.

Property	Wall Insulation	Pre intervention U-values (W/m²K)	Post intervention U-values (W/m²K)	% Improvement
Five Tenement Flats, Edinburgh	Polystyrene beads, 40mm, blown into cavity between internal plaster linings and external masonry walls	1.6	0.8	50%
	Polystyrene beads, 45mm, blown into cavity between internal plaster linings and external masonry walls	1.4	0.7	50%
	Polystyrene beads, 100mm, blown into cavity between internal plaster linings and external masonry walls	0.5	0.4	20%
	Aerogel, 10mm, plastered on hard.	-	0.8	-
Wells o' Wearie	Cellulose insulation blown behind lath and plaster (average post intervention U-values)	1.3	0.7	46%
	Aerogel 10mm behind plaster	1.4	1.0	29%
Wee Causeway	Calcium silicate board, 15mm thick, applied to inner face of external walls and plastered	1.5	0.7	53%
	Polystyrene beads blown into cavity between internal plaster linings and external masonry walls	1.5	0.5	67%
	Aerogel 10mm applied to inner face of external wall and plastered	1.6	0.9	44%
Sword Street	Blown polystyrene beads 50mm	1.1	0.32	71%
	Blown cellulose 100mm	1.1	0.29	74%
	Hemp insulation 100mm	1.1	0.22	80%
	Wood fibre board 80mm	1.1	0.19	83%
	Aerogel 40mm	1.1	0.37	66%
	Aerogel 50mm	1.1	0.32	71%
Kildonan	Wood fibre board 100mm	2.1	1	52%
	Calcium silicate board, 50mm thick, applied to inner face of external wall and plastered	2.1	0.4	81%
Rothesay	Aerogel 10mm applied to inner face of external wall and plastered	1.3	0.6	54%
Kirkton of Coull Farmhouse	Cellulose insulation blown behind existing plaster linings (average U-values)	1.4	0.15	89%
Annat Road	Icynene	1.1	0.41	63%
Downie's Cottage	Insulated lime plaster to inner face of external masonry, applied on the hard	1.8	1.1	35%
Lauriston Terrace	Polystyrene beads blown behind lath and plaster	0.57	0.3	47%
	Average	1.32	0.55	58.3%

Table 3: Range of wall insulation types and performance improvements.

Findings from the case study reviews

Regaining access to inspect the condition of new wall insulation behind new finishes was difficult. An endoscope inspection was possible at Wells o' Wearie (blown cellulose insulation) which indicated localised voiding in the cavity. At the same property, it was possible to observe in the roof space where cellulose material had escaped through gaps at the top of the wall cavity, resulting in an accumulation of insulation above (Figure 7). In the case studies where wall cavities were filled, it was reported that much emphasis was placed on ensuring gaps at floor level were filled to prevent leakage into the underfloor void. It may be that similar consideration is needed at ceiling levels.

Figure 7: Blown cellulose insulation deposited in the attic space at Wells o' Wearie.

At one of the tenement flats in Edinburgh, at Roxburgh Street, mould growth was visible on one of the walls injected with polystyrene beads, possibly an indication of a cold spot due to voiding in the cavity (Figure 8). Here, loose cavity insulation was reported by the tenant. Similarly, at Scotstarvit Cottage, where loose perlite was poured into the cavities behind the plaster linings from above in the roof space, localised leakage was visible through a gap between the floor and skirting. Indicative thermal imaging suggested that voiding and/or slumping may be affecting the performance of the insulation in this area.

At Kirkton of Coull (blown cellulose insulation), poor external water management had resulted in dampness internally at ground level in the area where cavity fill insulation had been injected (Figure 9). If the building is well maintained and kept in good condition, however, such problems are unlikely to manifest.

Figure 8: Mould growth (outlined in red) on the wall at Roxburgh Street, Edinburgh.

Figure 9: Poor rainwater management in south-east corner of Kirkton of Coull corresponding with area on dampness noted internally in living room.

Different methods of installing wall insulation have varying levels of impact on the building. The least invasive is filling the cavity between the existing internal linings and masonry behind, albeit generally this requires injection holes to be drilled which may be undesirable in properties with significant decorative schemes. Similarly, the fitting of surface applied insulation onto existing internal finishes will cover them and have an impact on surrounding services, joinery finishes such as skirtings and architraves, and plaster cornices.

Other forms of insulation which are installed behind internal linings, such as rigid boards, wood fibre and hemp, will result in high levels of disruption by the very nature of their installation. These more disruptive installations were restricted to projects where the previous internal finishes were already lost, compromised or could be easily dismantled and re-assembled, such as timber linings around window openings.

2.2 Roof insulation

Twelve of the eighteen case studies had roof insulation upgrades. Sheep's wool, hemp, wood fibre board and mineral wool were fitted into accessible roof spaces. This created cold roof spaces (Figure 10) in nine of the properties, and warm roof spaces (Figure 11) at Annat Road, Newtongrange and Kildonan where the insulation was fitted to the pitch of the roof to create warmer, more useable attics. Polystyrene bead insulation was blown into the voids behind sloping ceilings (cooms) at the Pleasance, Newtongrange and Kirkton of Coull. Additionally, aerogel blanket was fitted to the underside of an existing ceiling within a sloping ceiling at Kirkton of Coull.

Figure 10: Sheep's wool insulation forming a cold roof at the Garden Bothy in Cumnock.

Figure 11: Wood fibre board insulation creating a warm roof at Annat Road.

Thermal performance: Comparison of pre- and post-intervention U-values

Pre- and post-intervention sets of U-values for roof insulation were recorded and reported upon in nine of the case studies, averaging an improvement of 66% in thermal efficiency (Table 4). Significant improvements were demonstrated using sheep’s wool (up to 86%), hemp (87%) and wood fibre (up to 86%), which meets the Scottish Government’s Building Standard guidance for maximum U-value of 0.25 W/m^2K for conversion of heated buildings. The bonded polystyrene bead insulation used behind the sloping coom at Newtongrange also met the guidance, although this was later removed due to ventilation issues which resulted in mould growth on the underside of the sarking boards. Aerogel, applied to the underside of the ceiling finishes at Kirkton of Coull, while not meeting the same standard, did meet the ‘Individual element’ U-value of 0.35 W/m^2K given in the guidance.

Property	Roof Insulation	Pre intervention U-values (W/m²K)	Post intervention U-values (W/m²K)	% Improvement
Wells o' Wearie	Sheep's wool insulation 280mm	1.4	0.2	86%
Wee Causeway	Hemp insulation 250mm	1.5	0.2	87%
The Pleasance	Polystyrene beads blown into cavity behind coom	1.5	0.4	73%
Kildonan	Wood fibre board 50mm to coom	1.6	0.8	50%
	Wood fibre board 100mm to ceiling	1.9	0.4	79%
	Aerogel, 10mm, to dormers	1.7	1.2	29%
Leighton Library	Wood fibre insulation 200mm	1.3	0.2	85%
Newtongrange	Sheep's wool insulation 240mm	1.6	0.4	75%
	Bonded polystyrene beads blown into cavity behind coom	1.9	0.4	79%
Kirkton of Coull	Wood fibre board insulation 80mm to dormers	0.45	0.37	18%
	Aerogel, 11mm, applied to inner face of existing plaster finishes (average U-values)	0.49	0.32	35%
Annat Road	Wood fibre board insulation 100mm (average U-values)	1.0	0.14	86%
Downie's Cottage	Wood fibre board insulation laid over attic floor.	4.0	1.1	73%
	Average	**1.56**	**0.47**	**66%**

Table 4: Range of roof insulation types and performance improvements.

Findings from the case study reviews

Where access was possible, inspections generally found all new roof space insulation to be well fitted, apparently performing well and contributing to improving thermal efficiency, with improved comfort levels and lower energy bills for occupants. Its installation was found to be generally non-invasive in nature, with minimal impact on the character of any of the properties inspected.

However, several issues were identified. High moisture levels in roof timber and/or mould growth were observed in four of the case studies, all seemingly related to a lack of ventilation within the roof space. At Wee Causeway (Figure 12), Kirkton of Coull and Newtongrange ventilation levels were much reduced due to the use of impervious underfelts beneath the external roof finishes, exacerbated at the latter two properties by the insertion of blown insulation above the sloped ceilings of the first-floor rooms beneath.

Following a period of monitoring, moisture levels at Newtongrange have returned to normal since the insulation was removed and a constant ventilation flow re-established.

At all three properties, plus the Garden Bothy (Figure 13), the presence of first floor bathrooms and a lack, or poor positioning, of mechanical extraction, appear to be contributing factors to vapour entering the roof spaces. At Wee Causeway high moisture levels in the attic space were also exacerbated by dampness in the masonry. At this property there have since been significant improvements following fabric repairs to the masonry, installing discreet roof ventilation and fitting a new mechanical extract fan in the bathroom.

Figure 12: Mould visible on underside of sarking boards in an unventilated roof space following installation of insulation at Wee Causeway.

Figure 13: Higher moisture levels recorded on the underside of the sarking boards in the area over the shower room at the Garden Bothy.

Elsewhere, displacement of insulation and/or not maintaining a consistent air gap at eaves level were visible at Wells o' Wearie and Scotstarvit Cottage, which despite not having a major impact on the condition of the property at the time of inspection, may have longer term implications (Figure 14). Similarly, uninsulated water tanks and associated pipework located above the newly laid insulation at Wells o' Wearie and the Garden Bothy could result in future flooding if subjected to freezing temperatures (Figure 15). In addition, mould growth visible on internal plasterwork around the loft hatch at Wells o' Wearie may be a result of the loft access hatch not being insulated, creating a cold spot in this area (Figure 16).

Figure 14: At Scotstarvit Cottage there did not appear to be any air gaps at eaves level to encourage ventilation in the roof space.

Figure 15: Uninsulated cold water storage tank and associated pipework at the Garden Bothy, which could cause problems if subjected to freezing temperatures.

Figure 16: Surface mould in the hallway around the uninsulated loft hatch cover at Wells o' Wearie.

2.3 Floor insulation

Seven case studies included floor insulation upgrades. Hemp and wood fibre insulation products were fitted between joists of existing suspended timber floors (Figure 17), aerogel blanket was laid over an existing concrete floor, and in two properties (Downie's Cottage and the Garden Bothy), insulated lime concrete was specified (Figure 18).

Figure 17: Wood fibre board insulation being installed to a suspended timber floor (Photo courtesy of Historic Environment Scotland).

Figure 18: Insulated lime concrete being laid at Downie's Cottage (photo courtesy of Historic Environment Scotland).

Thermal performance: Comparison of pre- and post-intervention U-values

Pre-and-post intervention floor U-values were recorded and reported upon for four of the case studies, averaging an improvement of 78% in thermal efficiency (Table 5). Wood fibre averaged 73% at a depth of 80mm, with final U-values of 0.7 W/m^2K at Wells o' Wearie and 1.0 W/m^2K at Kirkton of Coull. Aerogel laid 30mm thick improved the U-value at Kildonan by 79%, the post-intervention values were recorded at 0.8 W/m^2K. At Downie's Cottage 100mm of insulated lime concrete was installed, creating an 87% improvement in the U-value which was recorded at 0.5 W/m^2K. None of these approaches met the Scottish Government's Building Standard guidance for maximum U-value of 0.25 W/m^2K for conversion of heated buildings, although the 'Individual element' U-value of 0.7 W/m^2K given in the guidance was met by the 80mm of wood fibre fitted between joists at Wells o' Wearie and the insulated lime concrete at Downie's Cottage.

Property	Floor Insulation	Pre intervention U-values (W/m^2K)	Post intervention U-values (W/m^2K)	% Improvement
Wells o' Wearie	Wood fibre insulation, 80mm	2.4	0.7	71%
Kildonan	Aerogel, 30mm, to existing solid floor	3.9	0.8	79%
Kirkton of Coull Farmhouse	Wood fibre board insulation 80mm	4.0	1.0	75%
Downie's Cottage	Insulated lime concrete 100mm, laid over underfloor heating pipes	4.0	0.5	87%
	Average	**3.58**	**0.75**	**78%**

Table 5: Range of floor insulation types and performance improvements.

Findings from the case study reviews

As with inspecting wall insulation upgrades, opening up floors to inspect insulation was not possible. The significant U-value improvements reported in the case studies, however, correspond with positive feedback from occupiers who noticed a significant reduction in draughts. No obvious defects associated with new floor insulation were visible at the time of survey. However, there are risks that high external ground levels, poor drainage and blocked-up underfloor ventilation (Figure 19), as visible at Well's o' Wearie, Scotstarvit Cottage and Kirkton of Coull, could cause dampness and compromise the insulation's effectiveness.

Figure 19: Raised external ground levels and partially blocked underfloor ventilation, as identified at Kirktoun of Coul, can compromise natural airflow into the underfloor space which increases the risk of damp related problems such as condensation and timber decay.

Unless floorboards can be accessed from underneath, installing insulation between floor joists necessarily results in disruption to the floorboards. However, careful lifting and relaying resulted in minimal impact on fabric or character in these case studies. Overlaying existing floor finishes with aerogel, while resulting in less disruption, has the potential to raise floor levels, affecting joinery finishes and door openings.

2.4 Windows

Works to windows were specified in ten of the case studies reviewed. These comprised secondary glazing installations, upgrading existing windows with new high-performance double glazing and/or improved insulated shutters, or installing new and appropriately matching windows. In each case the aim was to demonstrate the possibilities of improving thermal efficiency while preserving the character of the buildings by retaining, or closely matching, their original windows (Figure 20).

Figure 20: The installation of secondary glazing in Rothesay allowed the original timber sash and case window to be retained but has proved cumbersome to operate.

Thermal performance: Comparison of pre- and post-intervention U-values

Pre- and post-intervention window U-values were recorded and reported upon for three of the case studies (Table 6). In window upgrades to five Edinburgh tenement flats, three sets of readings were taken on different secondary glazing specifications, averaging an improvement of 81% in thermal efficiency. Timber double glazed secondary glazing recorded a U-value of 0.6 W/m^{2}K compared with 1.5 W/m^{2}K for single glazed secondary glazing. Both meet the Scottish Government's Building Standard guidance for maximum U-value of 1.6 W/m^{2}K for conversion of heated buildings. Further thermal efficiency was demonstrated where timber window shutters were upgraded by fitting aerogel blanket into recessed panels.

The installation of polycarbonate secondary glazing, a much simpler and less expensive method of installation, reduced U-values at Wells o' Wearie from 5.4 to 2.4 W/m^{2}K, an improvement of 56%, which meets the 'Individual element' U-value of 3.5 W/m^{2}K given in the guidance.

The installation of new double glazed panes within the existing timber sash and case windows at Archibald Place, Edinburgh, reduced the average U-value from 4.4 to 2.6 W/m^{2}K, an average improvement of 41%. The installation of Pilkington energiKare was the most efficient with a U-value of 1.9 W/m²K, an improvement of 57%.

Property	Windows	Pre intervention U-values (W/m²K)	Post intervention U-values (W/m²K)	% Improvement
Five Tenement Flats, Edinburgh	Secondary glazing, double glazed with aluminium frame to existing single glazed timber sash and case	5.4	0.8	85%
	Secondary glazing, double glazed with timber frame to existing single glazed timber sash and case	5.2	0.6	88%
	Secondary glazing, single glazed with timber frame to existing single glazed timber sash and case	5.2	1.5	71%
	Aerogel, 10mm, blanket fitted to timber window shutters	2.2	0.4	82%
Wells o' Wearie	Polycarbonate secondary glazing held with magnetic strips	5.4	2.4	56%
Archibald Place, Edinburgh	Sashworks argon filled double glazing	4.4	2.5	43%
	Histoglass (D11, krypton filled)	4.4	2.8	36%
	Histoglass (D10, krypton filled, hand drawn outer pane)	4.4	2.6	41%
	Pilkington energiKare Legacy	4.4	1.9	57%
	Slimlite (air filled)	4.4	2.9	34%
	Slimlite (xenon and krypton fill, crown outer effect)	4.4	2.6	41%
	Slenderglaze (xenon and krypton fill)	4.4	2.3	48%
	Slimlite (xenon and krypton)	4.4	2.7	39%
	Average	**4.5**	**2.2**	**55%**

Table 6: Range of window intervention types and performance improvements.

Findings from the case study reviews

While the reported U-value improvements demonstrate the effectiveness of the case study interventions, the inspections carried out revealed mixed findings. At Russell Street in Rothesay and Newtongrange (Figure 21), the secondary glazing installed during the refurbishments has since been removed and replaced with new timber double glazed sash and case windows, which are a reasonable but not exact match for the existing windows. The new windows have horns and a different glazing bar profile, details which detract from the traditional uniformity of the street frontage. In both cases, the windows were replaced partly in response to tenants complaining that, despite the introduction of secondary glazing, comfort levels and/or condensation continued to be a problem. Condensation in windows is caused, however, by high levels of internal humidity, and so improved ventilation regimes should also be considered.

Figure 21: On the right, new timber sash and case double glazed windows installed at Newtongrange. Although broadly similar to the original windows, they are not an exact match.

The Edinburgh tenement flats upgraded with new bespoke secondary glazing were found to be in a sound condition, with only minor failure of the ironmongery reported. Mould growth was visible on the window joinery and curtains in the flat upgraded with single glazed secondary glazing, probably caused by a lack of ventilation (Figure 22).

Figure 22: Mould growth on the windows of one of the tenement flats upgraded in Edinburgh, likely due to a lack of ventilation.

Three properties were upgraded with polycarbonate secondary glazing, which is fixed to the inner face of the existing window casement by magnetic strips. At Kildonan this secondary glazing has been removed and replaced with new timber sash and case windows to the owner's preference. At Wells o' Wearie and Scotstarvit Cottage, while window upgrades have improved thermal comfort for occupants, problems have arisen due to failure of the magnetic strips (Figure 23). In both cases, although feedback was generally favourable, the occupants had difficulties cleaning and storing the polycarbonate units over the summer when not required.

Figure 23: Failing magnetic strips on bottom sash rail around the secondary glazing at Wells o' Wearie.

One of the main aims of the window upgrades was to ensure that they did not adversely affect the character of the properties. In the Edinburgh tenement flats, where new bespoke secondary glazing was installed, despite the downtakings and alterations required before and during their installation, the visual impact on the property was minimal (Figure 24). Likewise, the impact of the secondary glazing fitted at Columshill Street in Rothesay and East Linton Primary School is minimal, albeit they were reported as being difficult to operate and awkward to gain access for cleaning the original sash and case windows behind.

At Archibald Place eight different types of replacement double glazing panes were installed into existing sash and case windows as part of trials to assess their thermal performance. The actual thermal performance of each was assessed by measuring U-values. The condition of the windows was inspected during the review and were found to be in good condition, with only minor issues such as jammed and poorly fitted sashes apparent. This, and many of the tenants being unaware of the need to naturally ventilate their flats, has resulted in instances of condensation. While the window upgrades all demonstrated an improvement in their thermal efficiency, their visual impact varied. Those retro-fitted with trickle vents, vacuum buttons or modern float glass (as opposed to undulating glass which imitates the character of historic glass), were more visually intrusive.

Figure 24: Bespoke secondary glazing in the Edinburgh tenement flats, which is almost imperceptible from ground level.

Despite the greater levels of thermal improvement demonstrated by the installation of bespoke secondary glazing, issues with condensation and difficulty of operation need to be considered when assessing their overall success. The impact of both these issues could be reduced by improved communications with occupants to demonstrate appropriate use of the windows and encourage natural ventilation when necessary to alleviate condensation.

2.5 Doors

Five case studies included door upgrades (Table 7). At three properties, existing doors were thermally improved by introducing a layer of aerogel blanket, which was covered over with plywood and decorated. Two properties had new doors specified: at the Garden Bothy a new front door with aerogel was fitted (Figure 25), and at Roxburgh Street, one of the tenement flats in Edinburgh, a bespoke timber rear door with eight double glazed panes was installed. Smoke and fire seals were fitted to existing internal doors at East Linton Primary School, which had the added benefit of reducing draughts.

Figure 25: The new front door for the Garden Bothy, insulated with aerogel.

Thermal performance: Comparison of pre- and post-intervention U-values

Pre- and post-intervention door U-values were recorded and reported in two of the case studies (Table 7), both following the upgrading of existing doors with a 10mm aerogel blanket fitted into recessed panels and covered with plywood prior to decoration. This produced significant improvements, reducing U-values to an average of 0.75 W/m^{2}K, an improvement of 78%, well within the Scottish Government's Building Standard guidance for maximum U-value of 1.6 W/m^{2}K for conversion of heated buildings.

Property	Doors	Pre intervention U-values (W/m²K)	Post intervention U-values (W/m²K)	% Improvement
Five Tenement Flats, Edinburgh	Aerogel blanket, 10mm, fitted within recessed panels and covered with plywood	3.0	0.7	77%
Rothesay	Aerogel blanket, 10mm, fitted to recessed panels	3.9	0.8	79%
	Average	**3.5**	**0.8**	**78%**

Table 7: Range of door interventions and performance improvements.

Findings from the case study reviews

Thermally upgrading doors has resulted in a significant improvement in their thermal performance. The new doors fitted at 16 Roxburgh Street and Garden Bothy are both well maintained and appear to be contributing greatly to improving comfort levels at these properties. However, the performance of the door upgraded at Russell Street in Rothesay (Figure 26) is compromised by poor maintenance, which has resulted in localised wet rot, and poor draught seals.

Figure 26: Russell Street, Rothesay. Despite recent re-decoration, the front door is in poor condition, with rot, damaged mouldings and poor preparation. The door remains draughty at the threshold.

The method of upgrading panelled doors by fitting an aerogel blanket into internal panel recesses and covering it with thin plywood has very little impact on the character of properties. If well maintained and carried out with effective draught proofing it can have a positive impact on comfort levels for occupants.

2.6 Heating

Heating upgrades were carried out at five of the eighteen case studies reviewed. Ground source heating and a biomass wood pellet boiler were specified at Downie's Cottage and the Garden Bothy, respectively. Infrared heating panels, which aim to provide thermal comfort to occupants at a lower ambient air temperature, thereby reducing utility bills, were specified at Scotstarvit Cottage (Figure 27), Annat Road and Kilmelford Parish Church. The infrared panels installed at the latter was part of larger heating trials, which also included air source heating, low wattage oil-filled tubular heaters, and convection heating, all implemented to improve both occupant comfort levels and internal environmental conditions for the health of the building. At East Linton Primary School a heat recovery system was installed in the roof space over the music room, to take advantage of a build-up of residual heat in this part of the building.

Figure 27: One of the heating panels used at Scotstarvit Cottage.

Findings from the case study reviews

The ground source heating installed at Downie's Cottage provides underfloor heating beneath a newly laid lime concrete floor, giving a constant low level of heat to the property. Although the plant and availability of land required to operate the system is sizeable, being able to provide a constant heat source has greatly benefitted the internal environment and fabric of the property.

The biomass boiler at the Garden Bothy has been removed since completion of the case study works and the date of the inspection. The property is now heated from a ground source district heating system which also serves neighbouring buildings in the adjoining walled garden area. As with Downie's Cottage, this provides a constant heat source which appears to benefit both the fabric of the building and its occupants.

The heating trials at Kilmelford Church are reported to have improved comfort levels for its users and have reduced utility bills. However, it is debatable whether the new heating has benefitted the fabric, one of the intended aims for its installation. The heating regime for the church currently comprises the air source heating system providing two hours of heat each morning at 16°C, with the remaining radiant, oil filled and convector heaters only operated when the church is used. Consequently, the internal environment of the church generally appears to be cold and damp, exacerbated further by poor building maintenance and lack of other thermal efficiencies, as well as high ground levels around the church which are causing penetrating damp. Repairing external defects, monitoring the internal environment and running the air source heating for longer periods could all be implemented to try and improve conditions at the property. The installation of the various heaters has had a considerable visual impact on the interiors of the church, and may be considered problematic in properties with significant interiors (Figure 28).

Figure 28: Kilmelford Parish Church, where a range of heaters, including oil filled, air source and radiant panels, were installed as part of trials which aimed to improve the quality of heating for the building and its occupants while reducing energy consumption. However, the visual impact is considerable and gives rise to a cluttered appearance.

The installation of new radiant panel heating at Scotstarvit Cottage sought to improve comfort levels and reduce utility bills. Despite initial teething problems which resulted in the tenant not being able to operate the new system effectively, the radiant panels are reported to be fully operational and remain in good condition. Despite this, the tenant still complains of occasionally feeling cold. Part of the problem appears to arise from initial claims from the supplier of the radiant panels that this form of heating alone would provide occupants with sufficient comfort levels. However, these claims are at odds with research reported in Historic Environment Scotland's *Technical Paper 14: Keeping Warm in a Cooler House*, which suggests that radiant panels should be used as a supplementary source of heating in a house which is already heated by other means to a temperature of around 16°C. In this case, restoring the use of open fires, as suggested by the tenant, should be considered on a trial basis.

A radiant panel was installed as a secondary source of heating in the bathroom at Annat Road to help control environmental conditions and is reported by the tenant to be successful in reducing condensation (Figure 29). The impact of the radiant panels on the character of the domestic properties where they have been installed has been minimal. Being surface mounted they are reversible, with only screw holes visible.

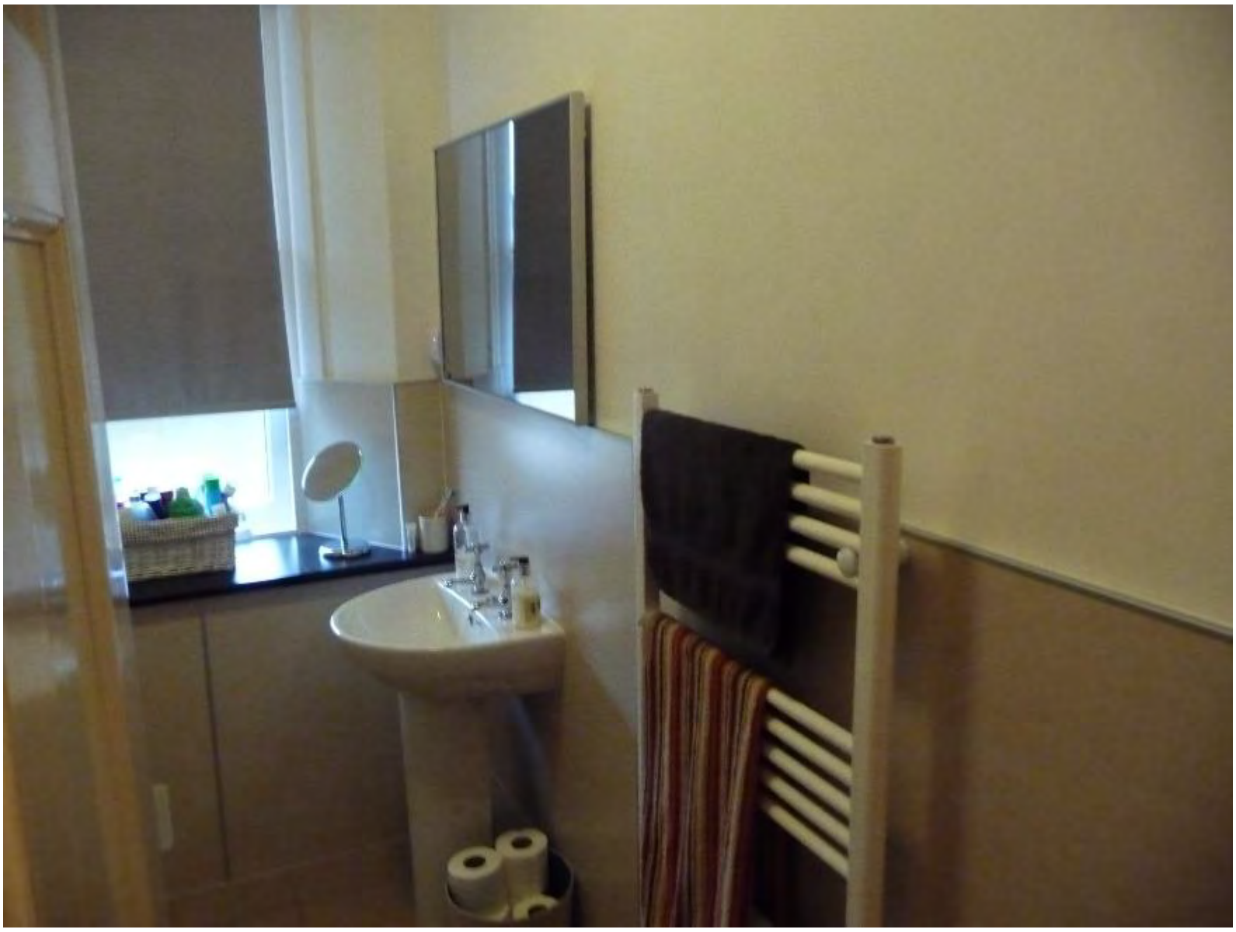

Figure 29: The radiant panel mirror installed in the bathroom at Annat Road.

During the inspection carried out at East Linton Primary School, while the heat recovery system was operating, the staff present were not aware of how it is controlled and generally complained about the poor internal environment within some of the classrooms. This is being exacerbated by a lack of natural ventilation due to impeded access to the sash and case windows caused by the new secondary glazing.

2.7 Other relevant interventions

Other interventions included the introduction of chimney balloons at Wells o' Wearie to minimise down-draughts during winter months (Figure 30), and improving natural ventilation at Annat Road. These interventions were found to be having a positive impact on the properties.

Figure 30: The chimney balloon used at Wells o' Wearie to help with down-draughts in the winter.

At East Linton Primary School, draught curtains were installed and draught lobbies created to improve comfort levels within the school. At the time of the inspection, gaps around the draught curtain were reducing its impact. The benefit of creating lobbies to allow pupils to access different parts of the building without creating draughts was also being compromised by a door being wedged open, apparently symptomatic of staff not being aware of the aims of the improvements carried out.

3. MONITORING AND ANALYSES

As well as recording pre- and post-intervention U-values throughout the implementation of the projects, a range of other monitoring and testing was carried out to determine the performance of the interventions and their impact on the internal environment and fabric of the properties. These are described in more detail below.

3.1 Moisture monitoring

As part of the wall insulation trials at Sword Street, monitoring was carried out to assess if there were any changes in moisture levels within the masonry that may have resulted from the interventions (Table 8). This was measured using probes at the junction of the inner masonry and the insulation, and at a depth of 50mm into the masonry. The results demonstrated that none of the insulation measures led to a significant increase in moisture, at either the interface of the insulation and the wall, or within the masonry. These results were reported in the case study as demonstrating that insulation can be safely applied directly to mass walls without a vapour barrier.

The small rises in humidity recorded at Sword Street (Table 8) are consistent with increased levels recorded at Kirkton of Coull, where post intervention relative humidity increased by 4% in the external walls of the ground floor gables from an already high average of 83.5% to 87.5%. This is likely due to reduced air flow within the cavity behind the plaster linings.

Insulation type	Average relative humidity of room (%)	Average relative humidity at interface between wall and insulation (%)	Average relative humidity 50mm into the wall fabric (%)
100mm hemp board	52.1	65.2	66.6
80mm wood fibre board	20.7	61.7	58.9
50mm blown cellulose	21.9	14.8	14.3
50mm aerogel board	45.9	64.4	63.3
50mm bonded polystyrene bead	58.3	16.4	15.8

Table 8: Average humidity levels over an 18-month monitoring period at Sword Street.

Monitoring of relative humidity levels at Annat Road is ongoing where perceived high humidity levels are of concern and considered to be linked to a lack of ventilation. However, further analysis is required to investigate absolute humidity levels and compare internal and external humidity. The conditions at Annat Road coupled with humidity and mould within the roof spaces at Wee Causeway and Kirkton of Coull, highlight the link between a lack of ventilation and high moisture levels in traditional buildings.

3.2 Post-intervention air leakage testing

Following completion of the refurbishment works at Scotstarvit Cottage, the property was tested for air leakage using blower door testing which relies on any permanent points of ventilation, such as openings, being covered or closed. This gives a result in m^3 of air per hour per m^2 of surface area in the living space ($m^3h^{-1}m^{-2}$@50Pa). It was found that the air leakage had reduced from 16.9 ($m^3h^{-1}m^{-2}$@50Pa) to 10.7 ($m^3h^{-1}m^{-2}$@50Pa), which is far closer to the maximum air leakage of 10 ($m^3h^{-1}m^{-2}$@50Pa) recommended by the Scottish Building Standards. Undoubtedly this, and upgraded insulation levels throughout the property, have improved thermal comfort for the tenant who, notwithstanding uncertainties regarding the new heating, commented on how ‘draught free’ the cottage is despite a lack of floor coverings. Care should always be taken to ensure that airtightness is balanced with adequate ventilation.

3.3 Air temperature monitoring

The impact of the refurbishments was monitored at two properties by assessing differences between internal and external air temperatures, a measure of how thermally efficient a property is. At Kirkton of Coull, this showed a reduction in temperature fluctuation within one of the bedrooms upgraded with wall and floor insulation, demonstrating reduced heat loss and fewer draughts within the property. Similar monitoring at Annat Road showed a 5°C improvement between internal and external temperatures compared with a neighbouring unimproved house. The insulated property was able to maintain a 9 degree difference, while its neighbour only managed 4 degrees, demonstrating the efficiencies of the interventions carried out.

3.4 Energy performance certificate

Pre- and post-intervention Energy Performance Certificates (EPCs) were produced for Kirkton of Coull. The refurbishment works resulted in a modest improvement from Band F to Band E, which is still below the recommended Band D that let domestic properties must eventually achieve according to the Scottish Government's current energy efficiency standards. The case study identified the limitations of assessing older and traditional properties which seems to unfavorably affect their EPC band rating. The issue relates to the assessment method which involves standard assumptions that are inaccurate when applied to older buildings as they underestimate their thermal efficiency and do not consider the condition of the building. For example, the standard EPC model uses a U-value of 2.4, whereas the average pre intervention testing for masonry walls throughout the Refurbishment Case Studies was 1.27, almost half the value used in the EPC model. Poorly maintained masonry could be up to 30% less energy efficient than dry masonry[2].

A consequence of underestimating thermal efficiency is that it could result in over-specifying measures to meet defined standards. This increases the likelihood of impacting on the character and significance of traditional buildings. For example, having to introduce thicker levels of insulation in wall cavities which may necessitate the removal of original plaster linings and fittings.

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[2]Edwards, John, 'Back to Basics' RICS Building Conservation Journal December 2016/January 2017 pp. 28-9.

3.5 Thermography

Upon completion of the window upgrades for the tenement flats in Edinburgh, thermographic images showed significant thermal efficiency improvements compared with neighbouring properties (Figure 31).

Figure 31: The reduction of heat loss through the newly upgraded windows at Roxburgh Street, Edinburgh (marked in black) with unimproved windows on neighbouring properties.

Indicative thermography carried out during the case study review inspections showed thermal anomalies in the external masonry at Wells o' Wearie, the tenement flats in Edinburgh, Wee Causeway (Figure 32), and Russell Street in Rothesay. These could be caused by damp masonry, exacerbated by poor maintenance and cement based repointing, which tends to trap moisture. Although further investigation is required, it is probable that the improvements carried out at these properties are being compromised by excessive heat loss through damp walls which are less thermally efficient than dry, well maintained masonry. This shows the importance of undertaking energy efficiency improvements in the context of broader repair and maintenance issues, and taking a 'whole building' approach.

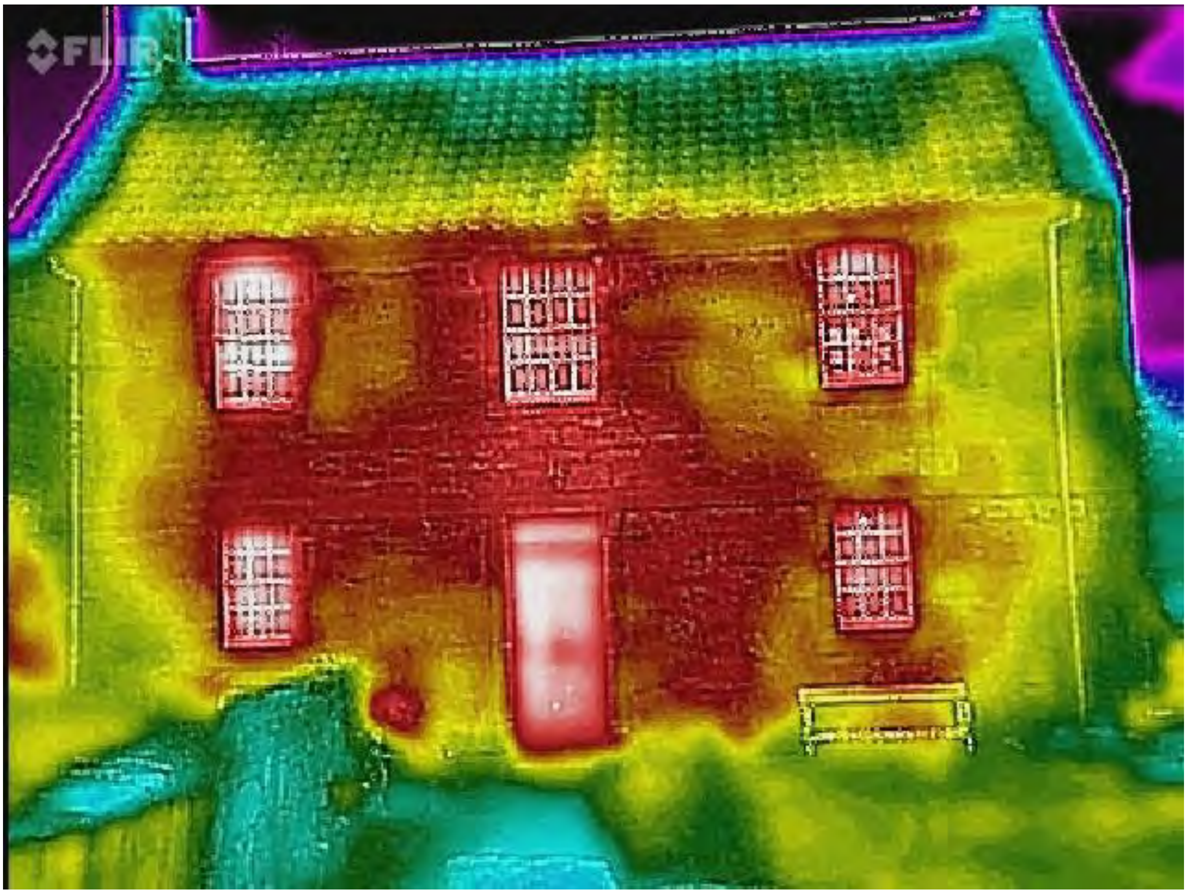

Figure 32: Wee Causeway, Culross, thermal anomalies indicate potential areas of heat loss particularly around windows and doors.

4. OCCUPANT FEEDBACK

Feedback from occupants on their comfort levels and energy bills before and after the refurbishment work was largely positive, with notable improvements reported. However, getting consistent feedback from those occupying domestic let properties proved difficult. This was partly due to many of the properties having a high turnover of tenants, and/or being unoccupied immediately prior to the works commencing. Similarly, assessing the impact of the refurbishments on the cost of energy consumption was difficult, as bills seem to be much affected by choice of supplier, variable tariffs and fluctuating oil/gas prices, making pre- and post-refurbishment comparison difficult. Where feedback was available, those occupying properties before and after the works generally reported lower bills. However, further research relying on unit based rather than price based consumption is needed to determine real impacts on energy use.

Those occupying properties both before and after upgrading works, generally reported an improvement in their thermal comfort, and at the least experienced no significant increase in utility bills. At Wee Causeway and Roxburgh Street in Edinburgh tenants who had moved into refurbished properties after the upgrades commented upon both significant savings and increased comfort levels compared with similar properties they had lived in before. These tenants also commented upon significant reductions in noise levels due to the window refurbishments. At the Pleasance, the tenant not only commented on reduced utility bills and warmer conditions in winter, but was also grateful that the roof insulation and new remote controlled rooflight made the property cooler in summer.

Such was the success of the work carried out at Kildonan that the property owner replaced the remainder of the uPVC windows with new timber double glazed sash and case windows similar to the specification used in the refurbishment works.

There was some negative feedback, which mostly related to a lack of information given to occupiers informing them of the refurbishment work and its aims and objectives. Improved communication and engagement can inform tenants how they can contribute to helping make traditional buildings more comfortable and habitable. For example, encouraging the tenants at Wee Causeway, Sword Street, Rothesay, Newtongrange and Archibald Place to ventilate their properties may have helped reduce the levels of condensation and mould growth reported. Similarly, the problems experienced by the tenant with the new heating system at Scotstarvit could have been overcome by clearer instructions and a better demonstration by the installers.

There was negative feedback on the secondary glazing installed at Newtongrange and Russell Street in Rothesay, with the tenants reporting little improvement in their thermal comfort and a tendency for condensation to form on the windows. Difficulty with operating and cleaning windows was reported at Roxburgh Street in Edinburgh, Columshill Street in Rothesay, Newtongrange and East Linton. At Columshill Street and East Linton Primary School, the secondary glazing restricted access to the sash and case windows, preventing them opening and thus impeding natural ventilation.

The occupants of properties which were well maintained were much more positive about the interventions. Those occupying properties in a poorer condition, despite the overall success of the refurbishment works carried out, tended to express higher levels of dissatisfaction.

5. CONDITION OF PROPERTIES

One of the objectives of the case study review was to comment on the condition of the properties and note if this was impacting on the performance of the refurbishment interventions.

There appears to be a clear link between the condition of a property and the success of the works undertaken. Properties which were reported to be well maintained and in good condition, such as Annat Road, Scotstarvit Cottage, Downie's Cottage and the Garden Bothy, are benefitting more from the interventions by minimising the impact of penetrating dampness.

Conversely, at several properties, there is evidence that a lack of maintenance is compromising the condition of the fabric and impacting on the performance of the interventions. This is most noticeable at Wells o' Wearie (Figure 33), Wee Causeway, Russell Street in Rothesay, Kirkton of Coull (Figure 34) and Kilmelford Church. In all these cases, the external masonry appears damp, exacerbated by cement based repointing mortar which is trapping moisture within the fabric and significantly reducing thermal efficiency compared with a well maintained dry wall. Underfloor ventilation at these properties was also compromised, with vents blocked up or partially covered, minimising natural ventilation and increasing the risk of condensation.

Figure 33: External masonry at Wells o' Wearie. The performance of the new wall insulation is being compromised by poor maintenance and inappropriate repairs resulting in damp walls which are less thermally efficient.

Figure 34: The masonry at Kirkton of Coull. As with Wells o' Wearie, damp masonry is compromising the performance of the new wall insulation. In this case the damp is likely to be exacerbated by the use of cement based pointing.

6. COST ANALYSIS

In order to assess the economic value of the retrofit measures, a simple cost analysis exercise was carried out which considered the costs and benefits of the interventions in the case studies (updated to 2017 prices) against the cost of conventional energy efficiency refurbishment approaches. All costs stated are approximate. The cost of many of the interventions were comparable with conventional approaches. Even those which appear to be much higher, such as the cost of installing new heating, can be partly recovered by cheaper running costs. Additional costs associated with installing natural vapour-open insulation should be evaluated alongside the longer term benefit to the building such as the reduced risk of damp related issues. In order to compare costs, recent energy efficiency upgrades completed at a HES property, Holyrood Park Lodge in Edinburgh, are considered here.

For cold attic spaces, the cost of 250mm sheep's wool, hemp or wood fibre insulation ranges between £26 to £30/m^2, compared with £8.50/m^2 for 250mm of mineral wool insulation. Typically, this would comprise 150mm of insulation laid between ceiling joists, with a further 100mm laid on top. 80mm wood fibre board cost around £30/m^2 at Kirkton of Coull and Holyrood Park Lodge. For warm attic spaces, where insulation is fitted between rafters, the cost of 100mm of wood fibre and 100mm of phenolic foam board is comparable at around £16/m^2.

Filling cavity linings with perlite (£64.14/m^2 at Scotstarvit Cottage), blown cellulose (£40/m^2, excluding filling and decoration) at the recently completed Holyrood Park Lodge project, and Icynene injection at Anatt Road (£51.75/m^2), compares favourably with stripping existing finishes and reinstating with insulated plasterboard/skimming (£52/m^2). From a conservation perspective this approach allows the retention of existing finishes. In cases where existing finishes can or have already been removed, insulating with wood fibre boards behind new plaster linings at Kirkton of Coull cost £57/m^2.

Similarly, fitting wood fibre floor insulation (£32/m^2), at Holyrood Park Lodge, excluding lifting and relaying floorboards is comparable with an equivalent approach using phenolic foam boards (£36/$m^{2)}$, including lifting and relaying floorboards.

When comparing the costs of different approaches taken for heating upgrades with a conventional oil fired central heating system, the Garden Bothy's Biomass heating system (£21,000) was significantly more expensive than oil (£11,000). The various heating measures introduced at Kilmelford Church (£21,500) also cost more compared with £17,000 for an oil fired system. Conversely, the radiant heating at Scotstarvit, albeit requiring a supplementary heat source, cost £6,200, significantly less than an oil fired central heating system of £12,000. The increased capital costs associated with the interventions should be at least partly offset by reduced on-going energy bills.

Bespoke secondary glazing ranged from £1,700 to £2,000 per window in the reported case studies, similar to the cost of replacing an entire window with new factory-made timber sash and case double glazed windows. Overhauling and upgrading existing sash and case windows, including routered draught seals, new slim profile double glazing and decoration is estimated to cost in the region of £1,000 per window, with overhauling and insulating existing window shutters an additional £600. Polycarbonate secondary glazing averaged around £265 per window at Scotstarvit.

7. CONCLUSIONS AND FINDINGS

The Refurbishment Case Studies were designed to demonstrate the effectiveness of using compatible materials in a way that minimises loss of historic building fabric, and maintains the vapour permeability of traditional buildings. The projects have demonstrated that it is indeed possible to implement significant energy efficiency measures to improve thermal comfort levels for occupants, without compromising the character and functionality of traditional buildings. They have also demonstrated that it is possible to meet the U-values recommended within the Scottish Government's Building Standards Technical Guidance for roofs, walls, floors, windows and doors, while also maintaining breathability and the vapour-open environment best suited to traditional buildings.

Improving the thermal efficiency of external walls, floor and doors within the case studies has largely been successful, with considerable reductions in U-value levels and improved thermal comfort for occupants achieved. The U-value measurements taken as part of this review confirm that the current method of assessing the Energy Performance Certificate rating of traditional buildings underestimates their thermal efficiency. This could potentially result in over-specification of retrofitting measures to meet new standards and to achieve a good rating. Over specifying increases the likelihood of impacting the significance and character of traditional buildings, as features and fittings are damaged or removed to accommodate thicker levels of insulation which may not be required.

The case studies have shown that there is a range of viable options to upgrade and improve the thermal performance of existing windows without adversely affecting their visual appearance. Bespoke double glazed secondary glazing achieved the greatest reduction in U-values. However, it is relatively expensive and was not universally favoured by occupants due to difficulties with operation and cleaning, as well as ongoing condensation issues. These difficulties could be improved by engaging with occupiers to demonstrate how the windows operate, and how to minimise condensation through natural ventilation. Polycarbonate secondary glazing offers value for money, and seems most appropriate as a lower cost and short-term solution. The installation of visually acceptable slim profile double glazing units into well maintained and draught proof existing windows, where the principle of replacing the glazing has been accepted, appears to be relatively cost effective, achieving significant improvements in efficiency while maintaining the form of the original window. This approach, when implemented with thermally upgraded window shutters, further improved energy efficiency and helped reduce noise pollution, an additional benefit appreciated by occupants.

Controlled ventilation is essential, especially when the property's natural ventilation routes have been reduced. Instances of dampness recorded in roof spaces after insulation was fitted appear to link directly to a lack of ventilation, either resulting from the presence of impervious roofing underfelts and/or restriction of existing ventilation pathways. Ongoing monitoring and analyses will increase understanding of these links and their impact. There also appears to be a connection between poorly ventilated bathrooms resulting in high moisture levels in roof spaces directly above. Improved ventilation in roof spaces, the appropriate positioning of mechanical extract fans and encouraging occupiers to naturally ventilate their properties would likely improve conditions.

The results and feedback from the heating improvements and other research appear to suggest that traditional properties benefit from being constantly heated at a low temperature. This was demonstrated at Downie's Cottage, and at the Garden Bothy, both of which have ground source heating. Similar principles were adopted at Kilmelford Church and Scotstarvit Cottage, whereby efforts were made to provide improved comfort at lower temperatures. However, the heating regime implemented at Kilmelford Church, although ostensibly designed to provide a constant low level of heat which is supplemented by additional heaters when in use, is only operated for short periods. Scotstarvit Cottage also lacks a form of heat to provide any form of background (or supplementary) heating. While at Scotstarvit Cottage the significant thermal improvements have helped minimise the effects of this, at Kilmelford Church no other thermal improvements were implemented. Therefore heat loss is still rapid, and exacerbated by poorly maintained and damp external walls. Although the research presented here principally concentrates on the comfort of occupants, it seems likely that maintaining a low level of background heat would also benefit the fabric of traditional buildings. This is especially true if the background heat is coupled with improved insulation measures.

Improved communication with occupants such as explaining the aims, nature and benefits of the refurbishment works, along with the care and operation of the elements in question, is likely to increase the effectiveness of the refurbishments and minimise condensation and mould growth.

The costs associated with the interventions were not universally higher than conventional approaches and should be viewed alongside the longer-term health benefits to both occupants and buildings.

This review of the Refurbishment Case Studies has demonstrated that a well maintained building is more thermally efficient. For properties where the condition of the external fabric was poor and/or there was a lack of maintenance, these factors compromised the effectiveness of wall, door and floor upgrades. Occupants of well maintained properties gave more positive feedback on the interventions than those living in houses with defects such as damp external masonry.

NOTE

Since this review was carried out, additional U-value testing has been commissioned at the sixteen domestic properties. The results of this will be published in due course.

Remedial work has been carried out at Wee Causeway to improve the thermal performance of the external doors and improve ventilation to the roof and underfloor areas. As a result of this project review, Historic Environment Scotland is liaising with the property managers and owners of the case study buildings to provide advice and support on appropriate management of the buildings to maximise the benefit from the energy efficiency interventions.

REFURBISHMENT CASE STUDIES

This series details practical applications concerning the conservation, repair and upgrade of traditional structures. The Refurbishment Case Studies seek to show good practice in building conservation and the results of some of this work are part of the evidence base that informs our technical guidance.
All the Refurbishment Case Studies are free to download and available from the HES website www.historicenvironment.scot/refurbishment-case-studies

TECHNICAL PAPERS

Our Technical Papers series disseminate the results of research carried out or commissioned by Historic Environment Scotland. They cover topics such as thermal performance of traditional windows, U-values and traditional buildings, keeping warm in a cool house, and slim-profile double-glazing.
All the Technical Papers are free to download and available from the HES website www.historicenvironment.scot/technical-papers

INFORM GUIDES

Our INFORM Guides series provides an overview of a range of topics relating to traditional skills and materials, building defects and the conservation and repair of traditional buildings. The series has over 50 titles covering topics such as: ventilation in traditional houses, maintaining sash and case windows, domestic chimneys and flues, damp causes and solutions improving energy efficiency in traditional buildings, and biological growth on masonry.
All the INFORM Guides are free to download and available from the HES website www.historicenvironment.scot/inform-guides

SHORT GUIDES

Our Short Guides are aimed at practitioners and professionals, but may also be of interest to contractors, home owners and students. The series provides advice on a range of topics relation to traditional buildings and skills.
All the Short Guides are free to download and available from the HES website www.historicenvironment.scot/short-guides

THE ENGINE SHED

The Engine Shed is Scotland's building conservation centre. Run by Historic Environment Scotland, it is a hub for everyone to engage with their built heritage. We offer training and education in traditional buildings, materials and skills. For more information, please see our website at www.engineshed.scot

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Historic Environment Scotland is the lead public body established to investigate, care for and promote Scotland's historic environment.

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